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Abstract

Measurements of the galactic radio background at ~ 1 MHz by Alexander et al. (1970) imply that the intensity of low rigidity (~ 0.3 GV) electrons beyond the solar system is much greater than that directly observed near the earth. Taking this depression of intensity as arising mainly from a solar modulation applicable to all cosmic rays of comparable rigidity, it is shown that the flux of subrelativistic protons and alpha particles in the galaxy would be sufficient for heating the interstellar HI gas and providing the ionization needed for maintaining the large electron content indicated by pulsar dispersion measures. A non-uniform spatial distribution of galactic cosmic rays would be a consistent feature of this description.

Recent observations of the cosmic synchrotron radio noise at low frequency (Alexander et al., 1970) indicate that electrons of ~ 0.3 GV rigidity within the local region of the galaxy are at least an order of magnitude higher intensity than similar rigidity cosmic

ray electrons directly measured at ~1 A.U. from the sun. Since protons of like rigidity are subrelativistic (i.e., ~50 MeV) we reexamine, within the context of this new information, the point of view (Balasubrahmanyan et al., 1968) that a large flux of such highly ionizing particles in interstellar space could provide a consistent basis for both (1) the heating of interstellar HI gas, and (2) a strong exclusion of low rigidity particles from the inner solar system.

For rigidities in excess of ~10GV, the spectrum of cosmic rays observed at ~1 A.U. from the sun has been taken as representative of that immediately outside the solar system, beyond the region of solar modulation. At lower rigidities the situation is much less direct since the solar wind severely modulates this part of the spectrum (see Balasubrahmanyan, Boldt and Palmeira, 1965, 1967). For about five decades above 10 GV, the observed differential spectrum is consistent with a power-law of index ~2.5 (see review by Linsley, 1963). The simplest situation would have an extension of this power-law to lower rigidities, with the observed deviations arising mainly from solar modulation. However, in an extrapolation to a subrelativistic region of the spectrum there is an ambiguity about whether the appropriate independent variable is in fact rigidity <u>or</u> total energy <u>or</u> kinetic energy. Balasubrahmanyan et al. (1968) pointed out that an extrapolation in kinetic energy had the

crucial feature of providing enough ionizing power for such cosmic rays to keep the interstellar HI gas heated to the observed temperature of $\sim 10^2$ °K.

Figure 1 shows a source spectrum based upon a power law in kinetic energy, extrapolated from high energy observations. Also shown are the modifications to be expected (Balasubrahmanyan et al., 1968) for average interstellar traversals of $3g/cm^2$ and $6g/cm^2$, using an exponential path length distribution (Cowsik et al., 1967). The heating of the interstellar HI gas that would result from such spectra for cosmic ray protons and alpha particles (at 1/6th the proton flux) was evaluated. At 36 e.V. per ion pair, this heat input corresponds to a total ionization rate per hydrogen atom (ζ) given by

$$(1) \qquad \zeta = (1 - 2) \times 10^{-15}/\text{sec}$$

for the curves in Figure 1 labeled "$6g/cm^2$" and "$3g/cm^2$" respectively. This ionization rate is consistent with that recently determined by Hjellming, Gordon and Gordon (1969) as $(2.5 \pm 0.5) \times 10^{-15}$/sec., based upon correlated observations of the interstellar medium via 21 cm radio data for neutral hydrogen and pulsar dispersion measures of the ionization.

For rigidities of 0.3 - 1.0 GV, the interstellar spectra of Figure 1 were adequately well related to the observed spectrum by a semi-empirical expression of the form

$$\text{(2)} \qquad \frac{\text{(Interstellar Intensity)}}{\text{(Observed Intensity)}} = \exp\,(K/\beta)$$

where β is the particle velocity (units of c), and K is a solar modulation parameter that decreased by ~0.6 during the years 1961-1965 and is approximately independent of the particle kinematics. For 1965, a year of minimum solar modulation, this analysis by Balasubrahmanyan et al. (1968) yielded an estimate of the absolute magnitude of K, vis:

$$\text{(3)} \qquad K = 2.7 - 3.0$$

for interstellar spectra corresponding to the curves in Figure 1 labeled "$6g/cm^2$" and "$3g/cm^2$" respectively.

We now extend this description of solar modulation to electrons of like rigidity. Equations 2 and 3 (note that here $\beta \approx 1$) give the ratio of electron intensities as

$$\text{(4)} \qquad \frac{\text{(Interstellar Intensity)}}{\text{(Observed Intensity)}} = 15 - 20$$

for K = 2.7 and K = 3.0 respectively.

If we allow for a possible factor $\gtrsim 2$ in the spatial non-uniformity for the intensity of such electrons in the local region of the galaxy, then this ratio is consistent with the directly determined value $\gtrsim 40$ obtained by Alexander et al. (1970) for 0.3 GV electrons. We point out that the magnitude of solar modulation previously discussed for electrons (Ramaty and Lingenfelter, 1968) would give a ratio that is an order of magnitude smaller than this estimate (Equation 4).

The energy density for the interstellar spectra of Figure 1 are 3 e.V./cm^3 and 5 e.V./cm^3 for the curves labeled "6 g/cm^2" and "3 g/cm^2" respectively. These are higher than the value ~1 e.V/cm^3 indicated by Parker (1966) to be consistent with galactic disk containment of the cosmic ray gas and associated magnetic field. However, it is important to recognize that spectra comparable to those in Figure 1 need obtain only in HI regions of the galaxy where they provide the required input for heat balance. Since HI regions account for only ~6% of the space near the galactic plane (Allen, 1963), the energy density averaged over the entire galactic disk could be as low as 0.2 e.V./cm^3, if cosmic rays below ~10^6 GV are indeed preferentially associated with HI regions. An interesting feature of this possibility is the spectral steepening to be expected for rigidities where the Larmor radius ceases to be small compared with the radius of an HI cloud. Taking a radius of 8 pc for an HI cloud (Allen, 1963) and an interstellar magnetic field of 3 μG (Verschuur, 1969), the critical rigidity becomes ~10^7 GV. The observed cosmic ray spectrum does in fact steepen above a critical rigidity $\gtrsim 10^6$ GV (see review by Linsley, 1963) and so provides us with another consistent aspect of this picture for cosmic rays in interstellar space.

We emphasize that this explanation for the heating of the interstellar HI gas was constructed without recourse to the as yet

unobserved highly ionizing component of suprathermal nuclei at $\sim$2 MeV/nucleon recently postulated and extensively discussed in the literature (Spitzer and Tomasko, 1968; Field, Goldsmith, and Habing, 1969; Silk and Steigman, 1969). The steeply negative sloping component of the observed spectra for very low energy cosmic ray protons and alpha particles ($<$ 20 MeV/nucleon), discussed by Gloeckler and Jokipii (1967), has now been shown to be predominantly due to solar particles (Kinsey, 1970). The possibility that ordinary subrelativistic cosmic rays would be sufficient for heating the HI gas of the interstellar medium was anticipated by Hayakawa (1960) and Pikel'ner (1967) even before the experimental evidence to support this was presented by Balasubrahmanyan et al. (1968). As recently described by Boldt and Serlemitsos (1969), cosmic ray protons traversing the interstellar medium produce a well-correlated X-ray bremsstrahlung spectrum associated with the production of "knock-on" electrons. This X-ray signature is adequate for making a quantitative examination of the spectral and spatial structure for the flux of such subrelativistic cosmic rays throughout the galactic disk.

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Figure Caption

Figure 1: The curves "$< 3g/cm^2 >$" and "$< 6g/cm^2 >$" represent interstellar proton spectra obtained from the indicated power-law source spectrum on the basis of an exponential distribution of interstellar paths for mean traversals of $3g/cm^2$ and 6 g/cm^2 respectively (reproduced from Balasubrahmanyan et al., 1968).

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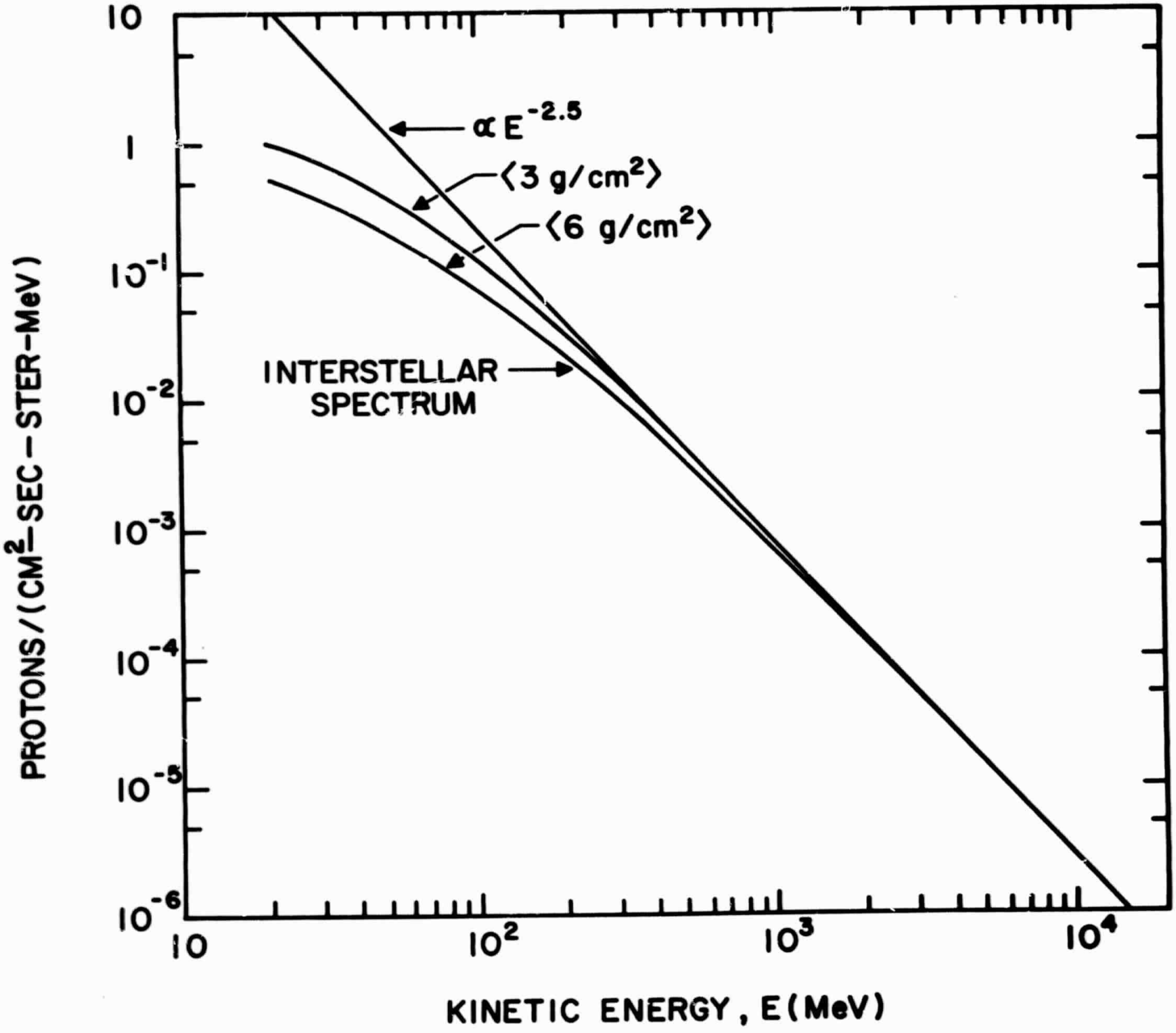

$\propto E^{-2.5}$
$\langle 3\ g/cm^2 \rangle$
$\langle 6\ g/cm^2 \rangle$
INTERSTELLAR SPECTRUM
PROTONS/(CM^2-SEC-STER-MeV)
KINETIC ENERGY, E(MeV)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
10^2
10^3
10^4